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AN OUT-OF-PLANE GALACTIC CARBON MONOXIDE SURVEY

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ABSTRACT

Galactic CO line emission at 115 GHz has been surveyed in the region $15° < l < 60°$ and $-1.^{\circ}5 \lesssim b \lesssim 1.^{\circ}5$. In addition to confirming the findings of previous in-plane surveys that galactic CO emission is concentrated in a ring 6 kpc in radius, a fit of a cylindrically symmetric galactic model to our observational data has provided the first determination of the thickness of this molecular ring and its displacement from the conventional galactic plane, both as functions of galactocentric distance. The average half-thickness at half-maximum of the molecular ring is 59 pc, and the average displacement of the ring with respect to the $b = 0°$ plane is -40 pc.
Subject headings: galaxies: Milky Way — interstellar: molecules

I. INTRODUCTION

Line emission by carbon monoxide is the best tool currently available to the radio astronomer for studying the dense molecular component of the Galaxy. Several recent surveys (Burton *et al.* 1975; Gordon and Burton 1976; Scoville and Solomon 1975) have demonstrated that the lowest rotational transition of this molecule at 2.6 mm can be detected along much of the galactic plane, and serves as an excellent tracer of galactic structure. These studies have revealed that the distribution of molecular clouds with respect to distance from the galactic center is markedly different from the distribution of H I—so much so that it has been suggested that molecular clouds and related objects (e.g., γ-ray sources, protostellar objects) can be regarded as a distinct population of galactic objects (Stecker 1976). However, except for a scan across the galactic plane at $l = 21°$ (Burton and Gordon 1976), these first CO surveys have been confined almost entirely to the galactic plane, and the thickness of the molecular disk is largely unknown. This *Letter* reports the results of the first systematic survey of CO line emission out of the plane, and the first determination of several important overall parameters of the Galaxy—in particular the thickness of the molecular disk as a function of distance from the galactic center, and the displacement of the molecular disk from the presently defined galactic equator.

II. OBSERVATIONS

The observations were made at Columbia University during the winter of 1975–1976 with a 4 foot (1.2 m) Cassegrain telescope whose full beamwidth at half power is 8′ at the CO frequency, 115 GHz. The superheterodyne receiver was a Schottky barrier mixer followed by a 50 K parametric amplifier operating at 1.4 GHz, giving a single-sideband system noise temperature of 1400 K. The spectrometer consisted of a filter bank with 1 MHz resolution (corresponding to 2.6 km s^{-1} at 115 GHz), and a total bandwidth of 40 MHz (104 km s^{-1}).

All data were taken by observing during alternate 30 s periods at the source position and at a comparison position. The comparison positions were checked with considerable care to ensure that they were free from CO emission. They were examined first by frequency switching; and if weak lines were suspected, they were further examined by position switching against verified "clean" positions. Comparison positions were typically 5° above and below the galactic plane, and 5° apart in longitude.

Baselines were removed from the raw data by fitting straight lines to emission-free parts of the spectra. When regions of the sky not containing CO were observed, this technique produced featureless spectra to the noise limit of the survey.

The receiver was calibrated against a room-temperature blackbody by a chopper wheel technique similar to that described by Davis and Vanden Bout (1973). Their method, which corrects for the beam efficiency and for the atmospheric attenuation in a single-layer atmosphere, was refined by using a two-layer model: an upper layer of O_2 and lower layer of H_2O (Chin 1977). The optical depth of the O_2 was calculated from a standard atmosphere; the optical depth of water was derived from antenna tippings made at least once every 6 hours. Observations were generally made on cold dry winter days when the optical depth of water was between 0.10 and 0.25 at the zenith. This calibration procedure gave corrected antenna temperatures that were self-consistent down to the lowest angles above the horizon at which observations were practical. The absolute calibration was checked on several astronomical sources against data taken with the NRAO 36 foot

(11 m) telescope at Kitt Peak. When spatially smoothed to our angular resolution, the intensity of the Kitt Peak spectra agreed to within 20% with the spectra from the 4 foot telescope.

Pointing was checked by radio continuum observations of the Sun and by optical observations of stars through a small finding telescope collimated with the radio beam. The maximum uncertainty in the pointing was 2′.

Observations of the Galaxy were made every 2°.5 in galactic longitude from 15° to 45° (except at 22°.5) and every 5° from 45° to 60°. At each longitude, observations were spaced 0°.25 (about two beamwidths) in latitude, and usually were extended above and below the plane until two successive positions showed no CO emission. Only positive velocities were observed, since previous in-plane surveys have shown that there is almost no CO emission at negative velocities for $l =$ 15°–60°. For $l < 40°$ the spectral range of our receiver does not cover the entire range of positive velocities allowed by the galactic rotation curve; and since observations were generally made at only one receiver setting, some CO emission was missed. Usually this was low-velocity emission corresponding to local CO, but at $l = 15°$, 17°.5, and 20° some weak CO emission found by Gordon and Burton (1976) was not surveyed. Integration times were adjusted to give a peak noise level of 3 $\sigma = 0.7$ K (corrected for atmosphere and beam efficiency) and typically varied between 20 and 40 minutes, depending on observing conditions. The total survey consists of 179 spectra.

Figure 1 is a summary of the observational data and shows the distribution of CO intensity at various galactic longitudes as a function of galactic latitude and radial velocity. Several of the more prominent molecular clouds are readily identified with well-known objects. For example, that at $l = 15°$, $b = -0°.8$, $v_{\rm LSR} =$ 20 km s^{-1} is M17; that at $l = 30°$, $v_{\rm LSR} = 95$ km s^{-1} is W43; and the large feature at $l = 35°$ is the W44 region.

Even without close analysis, the major features of the galactic distribution of CO are clear from Figure 1. First, there is little emission for $l > 45°$. As observations in these directions sample only points more than 7 kpc from the galactic center, we can conclude that most CO emission is located at $R < 7$ kpc. Also, for $l < 27°.5$ the emission has fallen to very low values at velocities less than the maximum permitted by the 21 cm rotation curve, indicating a sharp decrease in CO emission inside the $l = 27°.5$ tangent point, (i.e., for $R < 4.5$ kpc). Thus the CO is concentrated in a molecular ring about 2.5 kpc wide and centered at $R = 6$ kpc. Second, there is a distinct tendency for the CO to lie at negative b, suggesting that the mean CO plane is depressed below the standard plane. Third, the thickness of the plane is about 1° at high velocities near $l = 30°$, implying that the half-thickness of the disk is of the order of 60 pc in the molecular ring.

III. DISTRIBUTION OF CO EMISSION

In order to analyze the survey data more quantitatively, a severely idealized model of the Galaxy has been adopted. Specifically, it is assumed that the large-scale structure of the Galaxy is cylindrically symmetric, and that the only motion is circular rotation. The distance to the galactic center has been taken as 10 kpc, and the rotation curve derived by Burton (1971) from 21 cm data has been adopted (for $10 > R > 3$ kpc it lies within 3 km s^{-1} of the Schmidt curve, a negligible difference for present purposes).

The CO is assumed to be contained in many small clouds randomly distributed to give an average integrated volume emissivity (averaged over a volume containing many clouds, and integrated over line width) of

$$\epsilon(z, R) = \epsilon_0 \exp\left[\frac{-(z - z_0)^2(\ln 2)}{z_{1/2}^2}\right],$$

where z is the distance above the galactic plane. The central emissivity ϵ_0, the displacement z_0, and the thickness $z_{1/2}$ are functions of R that characterize the CO distribution. If, as argued by Burton *et al.* (1975), the clouds are sufficiently sparse that there is little shadowing of distant CO by nearer CO at the same velocity, then the intensity integrated over a single resolution element (channel) is simply given by the emissivity along the line of sight integrated over all positions containing CO at a velocity which falls in the channel.

To obtain the most likely values of the parameters $\epsilon_0(R)$, $z_{1/2}(R)$, and $z_0(R)$, the Galaxy was divided into concentric rings of width 0.5 kpc. In each ring the values giving the best least-squares fit of the data to the model distribution were then determined using a standard numerical code. Emission at forbidden velocities was insignificant, and consequently was ignored. In rings for which there were insufficient data to fit all the parameters accurately, the CO emission was assumed symmetric about the galactic plane (i.e., z_0 was constrained to zero).

The resulting parameters as functions of R are shown in Figure 2 with, for comparison, $z_{1/2}$ for H I (Jackson and Kellman 1974), and the in-plane intensity of CO emission of Gordon and Burton (1976). The error bars shown are internal errors in the fit, and apparently arise primarily from two sources: (1) the inadequacy of the model in representing the true structure of the Galaxy, and (2) random fluctuations in the distribution of molecular clouds. Except for $R < 3.5$ kpc, receiver noise contributes little to the uncertainties. When CO emission was constrained to be symmetric about the $b = 0°$ plane, $\epsilon_0(R)$ and $z_0(R)$ differed little from the values in Figure 2.

IV. DISCUSSION

As Figure 2*b* shows, the thickness of galactic CO is roughly constant in the region 5–7 kpc and agrees well with the thickness of other Population I objects, except H I (Burton *et al.* 1975). From 7 to 8 kpc, however, there is an apparent increase in the CO thickness by approximately a factor of 2. There is a proportional increase in the H I thickness in this region, but the H I thickness is about double that of CO. For CO, a weighted average of $z_{1/2}$, determined by weighting the values shown in Figure 2*b* for each ring by the area of the ring, yields $\langle z_{1/2} \rangle = 59$ pc.

The CO central emissivity $\epsilon_0(R)$ (Fig. 2*c*) is sharply peaked in the region of the molecular ring ($4 < R < 7$ kpc). This agrees rather well with the emissivity measured in the galactic plane by Burton *et al.* (1975), Gordon and Burton (1976), and Scoville and Solomon (1975). However, because the thickness of the galactic disk increases for $R > 7$ kpc, the total surface luminosity of the disk is not as sharply peaked as the previous in-plane surveys have implied, but instead is reasonably constant for $5 < R < 8$ kpc.

While the present out-of-plane survey and the in-

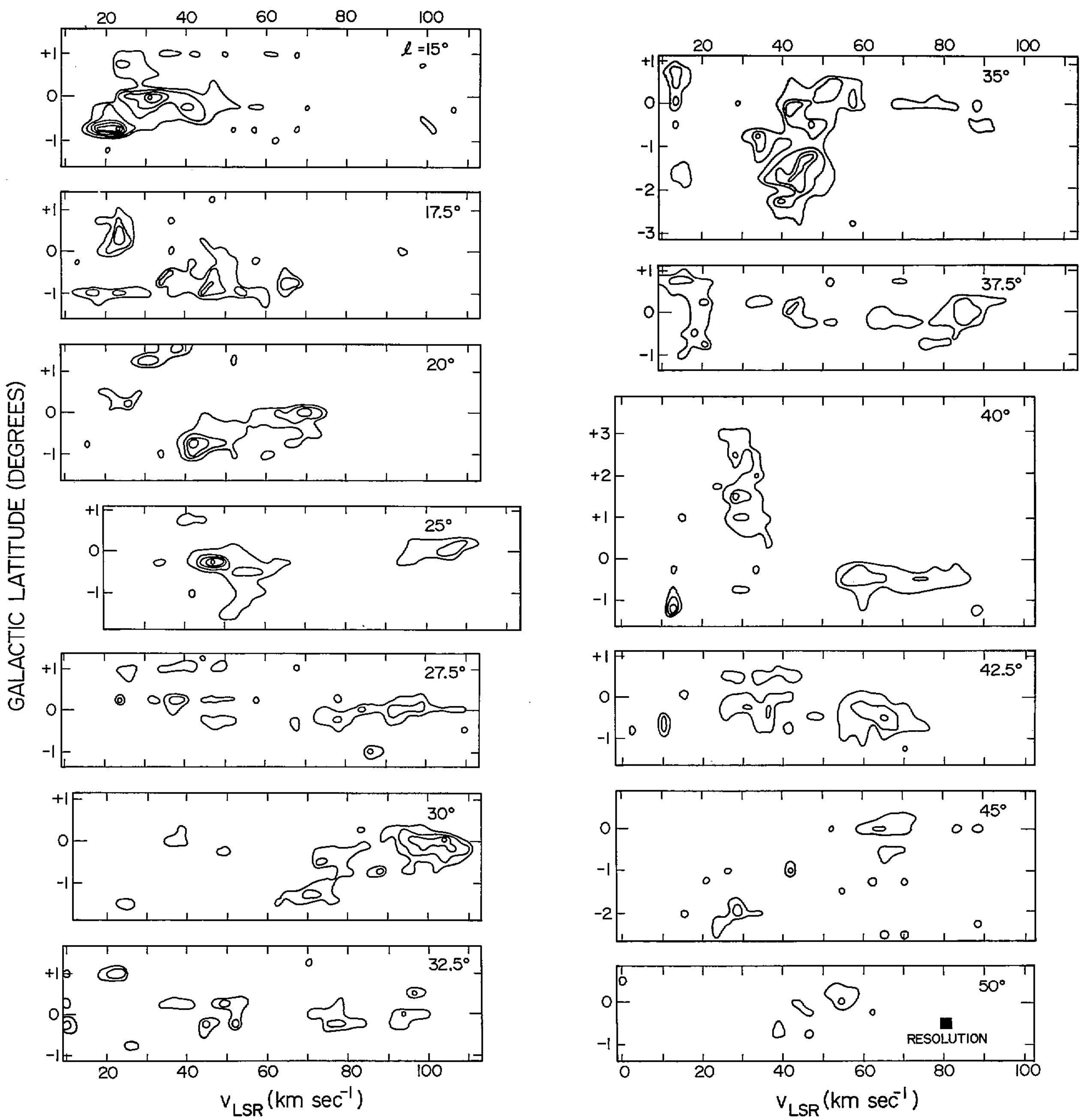

FIG. 1.—Distribution of CO emission in the galactic disk. The contour interval is 1 K antenna temperature (corrected for beam efficiency and atmosphere). The area of each plot shows the region actually surveyed in both velocity and latitude. The angular resolution indicated is that of the survey (2 beamwidths). Two additional longitudes were surveyed but showed no emission at the first contour level: $l = 55°$ from $b = -0.°75$ to $b = +0.°75$ and $v_{LSR} = 0$ to 104 km s^{-1}; and $l = 60°$ from $b = -0.°50$ to $b = +0.°50$ and $v_{LSR} = 0$ to 104 km s^{-1}.

plane surveys are all in good agreement on the shape of the distribution, no two agree on its absolute intensity. When antenna temperatures integrated over all velocities at a given longitude are compared, our results fall roughly a factor of 1.4 below those of Scoville and Solomon (1975), a factor of 2 below those of Burton *et al.* (1975), and a factor of 4 below those of Gordon and Burton (1976). Since the absolute calibrations of the 4 foot and NRAO telescopes agree reasonably well, this discrepancy does not appear to be an effect of calibration. The most likely explanation is the existence of a weak substratum of CO emission covering much of the positive-velocity region permitted by the rotation curve, and contributing most of the integrated intensity in the Gordon and Burton high-sensitivity survey, but not generally detected in the other surveys. Although

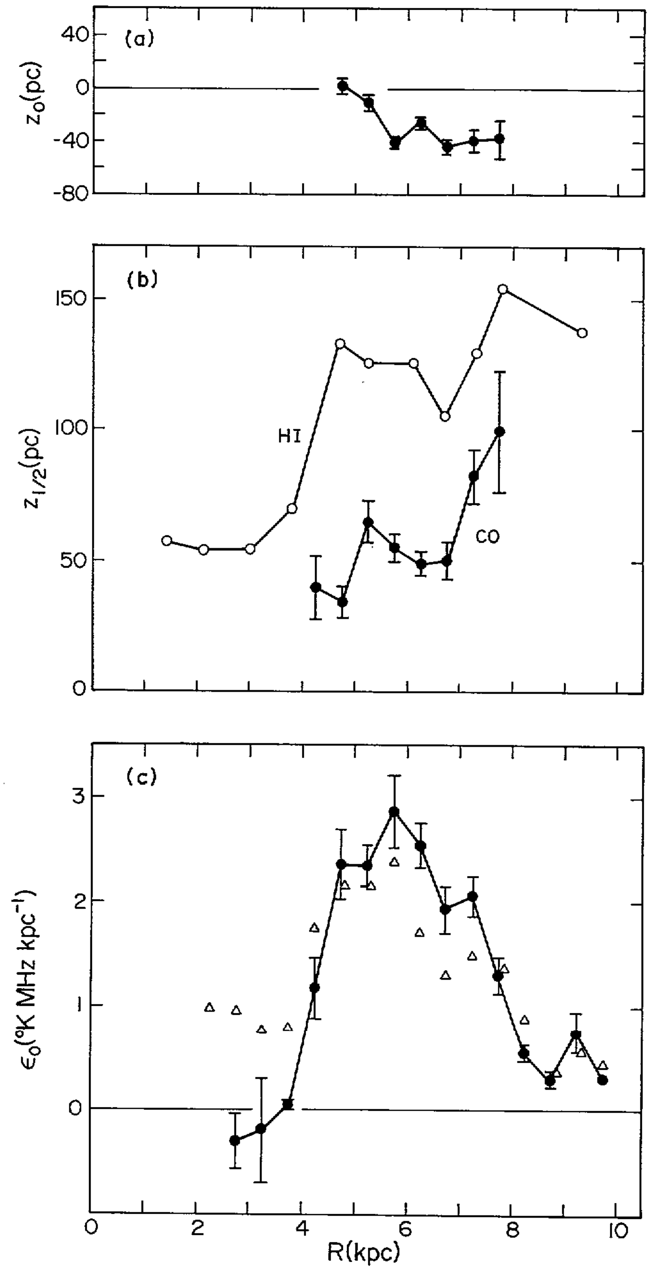

FIG. 2.—(*a*) Displacement; (*b*) half-thickness; and (*c*) centroid emissivity of the CO disk as functions of galactocentric distance. For the sake of comparison, measurements of the thickness of the H I disk as measured by Jackson and Kellman (1974) are shown in (*b*), and the CO in-plane emissivity (*open triangles*) as measured by Gordon and Burton (1976) is shown in (*c*), scaled down by a factor of 4.3 (see discussion in text).

we have not detected this weak emission, and the present survey is hence biased toward the more intense molecular sources, the close agreement in radial distribution of all the surveys strongly implies that the clouds we are seeing provide a reasonably faithful measure of the overall CO distribution.

The apparent discrepancy between our survey and that of Burton and Gordon when $R < 4$ kpc is possibly a consequence of undersampling in position and velocity, or a breakdown of the assumptions of circular rotation and circular symmetry. An extension of our survey with much finer coverage in longitude and a larger range in velocity is now under way, and should resolve this question.

The CO disk for $R > 5.5$ kpc seems to lie about 40 pc below the $b = 0°$ plane (Fig. 2*a*). As previously noted, the b, v contours (Fig. 1) suggest such a displacement over a wide range of longitudes, indicating that this effect is real and not the result of a single large complex south of the galactic equator. In order to verify that the offset does not depend on a small number of points, the fitting was repeated several times, each time with a substantial part of the data excluded from the fitting. Tests were made excluding (1) data for $l < 27.^{\circ}5$ where the depression of the plane is most apparent to the eye in the contour plots, (2) $l = 35°$ which contains a large complex below the plane, and (3) all points that made the survey asymmetric with respect to $b = 0°$. In none of these tests did the results change significantly. An examination of 21 cm surveys shows similar fluctuations in the mean z of the H I disk. In fact, the original determination of the new galactic plane by Gum, Kerr, and Westerhout (1960) shows fluctuations in the height of the H I density maximum of ± 25 pc inside the solar circle.

To sum up, an out-of-plane survey of CO line emission in the first quadrant of the Galaxy has confirmed the finding of previous in-plane surveys that CO is concentrated in a molecular ring about 6 kpc from the galactic center, and has furnished a determination of two other important properties of the molecular ring as a function of galactocentric distance, namely, the thickness of the ring, and its displacement with respect to the currently adopted galactic equator.

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REFERENCES

Burton, W. B. 1971, *Astr. Ap.*, **10**, 76.
Burton, W. B., Gordon, M. A., Bania, T. M., and Lockman, F. J. 1975, *Ap. J.*, **202**, 30.
Burton, W. B., and Gordon, M. A. 1976, *Ap. J.* (*Letters*), **207**, L189.
Chin, G. 1977, doctoral thesis, Columbia University.
Davis, J., and Vanden Bout, P. 1973, *Ap. Letters*, **15**, 43.
Gordon, M. A., and Burton, W. B. 1976, *Ap. J.*, **208**, 346.
Gum, C. S., Kerr, F. J., and Westerhout, G. 1960, *M.N.R.A.S.*, **121**, 132.
Jackson, P. D., and Kellman, S. A. 1974, *Ap. J.*, **190**, 53.
Scoville, N. Z., and Solomon, P. M. 1975, *Ap. J.* (*Letters*), **199**, L105.
Stecker, F. W. 1976, *Nature*, **260**, 412.

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